SUNSPOTS AND RAINFALL.

BY SIR NORMAN LOCKYER, K. C. B., F. R. S.

It was in 1801, just a century ago, that Sir William Herschel attacked the question, whether the price of wheat in England was in any way related to the appearance of many or few spots on the sun's surface. The inquiry then was a daring one; for, however perfect our national statistics may have been in relation to the price of wheat, there was nowhere kept up a continuous record of the changes visible on the sun's surface, nor had there been any serious attempt made to determine the law underlying them. Still, what data there were enabled Herschel to arrive at the conclusion that the price of wheat was highest when there were fewest spots.

We have to come down to Schwabe, and the year 1830, before that continuous record begins which soon revealed a cycle of eleven years in the solar changes; and down to Meldrum, and the year 1870, before these changes were studied in connection with changes in terrestrial weather. In the meantime, half-way between 1830 and 1870, in the year 1850, Lamont and Sabine discovered a very close connection between the amount of the sun's spotted area and the changes in terrestrial magnetism.

Meldrum and many others soon produced evidence indicating a similar, though not so obvious, connection with terrestrial weather: cyclones in the East and West Indies, and rainfall in certain places were shown to be at a maximum when the solar spotted area was greatest; and, in spite of cheap sneers on the part of scientific *fainéants,* this opinion gained ground among the thinkers. Among the difficulties of that time may be mentioned the absence of continuity in the records. Although De la Rue and Balfour Stewart had inaugurated a photographic registration of sun-spots at Kew, science had to be content each year with a record of about 150 days out of the 365. Rainfall regis-

tration was in its infancy, except at certain stations where observatories had been established; areas, therefore, could not be considered, especially in the tropics, where the atmosphere changes are the most regular.

But in the next few years a great improvement was effected. After reiterated appeals by Sir Richard Strachey to the Indian authorities, a Meteorological Department was established and began work in 1875; and, thanks to this organization, perfect rainfall observations have been made ever since, and in that very region of the world where they are of the greatest value for the study of meteorological changes, and where these changes, accompanied as they so often are by famines, lead to the most disastrous results.

While these efforts were being made in India, opinion at home was influenced by the "Indian Famines" report, in which it was stated that efforts should be made to do all that science could do in the way of securing a basis for possible predictions; and the Duke of Devonshire's Royal Commission on Science, which was then sitting, recommended the establishment of a Solar Physics Observatory in England, with branches in India and the Colonies, where the raw material, "sunshine," was much more plentiful than it is with us. A "Solar Physics Committee" was eventually appointed, and some wood and canvas huts were erected to cover a few instruments chiefly lent by the Astronomer Royal, Sir George Airy, and by private persons to carry on the necessary work.

As early as 1871, the Indian authorities were considering the question of erecting a Solar Physics Observatory in that country, in order that a complete record of solar changes might be secured to compare with the meteorological ones; but the proposal was abandoned on the ground of expense. It fell to my lot, however, to secure what was really needed in the first instance—namely, daily photographs of the sun. This was brought about by a personal appeal to Lord Salisbury, then Secretary of State for India, before the Solar Physics Committee was established. Thanks to this new organization, and to the subsequent addition of Mauritius as an observing station, the Greenwich photographs, which are a continuation of the Kew series before mentioned, have been so supplemented since 1878 that we may reckon on about 360 daily records in each year.

We have had, then, since 1875 a perfect record of the rainfall in India, and a perfect record of the sun's spotted area since 1878.

The first piece of routine work undertaken at the Solar Physics Observatory at Kensington, after the daily photographs of the sun had been so magnificently secured, was a daily examination of the spectra of sun-spots, in order to see if any light could be thrown by them on other solar changes connected with their formation. This has gone on regularly from the year 1879.

To explain this new branch of solar research, it may be stated that, on throwing the image of a sun-spot on the slit of a spectroscope, it is found that the spectrum of a spot so examined is not only darkened all along, but that certain of the Fraunhofer lines, observed in the ordinary spectrum of the sun, are *widened*, and that the lines widened vary from time to time.

One of the most important results of this line of inquiry, now that an examination of many years' records is available, shows us that the widened lines at some periods are easily traceable to known elements, while at others their origins have not been discovered; the latter, therefore, have been classed as "unknown" lines. If we compare these two periods with the sunspot curve, as constructed from the measurements of the mean spotted area for each year, it is found that, when the spotted area is greatest, the widened lines belong to the "unknown" class; while, when the spotted area is least, they belong to the "known" class.

Curves of the "known" and "unknown" lines have been made by determining for each quarter of a year the percentage number of known and unknown lines, and plotting these percentages. Instead of using the mean curves for all the known elements involved, that for iron is employed, as it is a good representative of "known" elements, and has been best studied. Such curves cross each other at the points where the percentage of unknown lines is increasing and that of the iron or known lines are diminishing, or *vice versa.*

It has been found that the chemistry of the spots changes with the sun-spot cycle. At sun-spot minimum, the spectral lines show that the spots contain iron vapor chiefly. At sunspot maximum, the iron lines disappear and are chiefly replaced by others about which we know nothing, as they have

not been recorded in any laboratory; the only reason so far suggested for this is that they indicate a very high temperature in the spot which we cannot reach in our laboratories. If we assume this, we have three stages of solar temperature thus indicated: a low temperature when the iron lines are seen alone; a mean temperature when the iron and unknown lines are equally mixed; and a high one when the unknown lines are seen alone.

When the curves of known and unknown lines cross each other—that is, when the number of known and unknown lines is about equal—we must assume a mean condition of solar temperature. When the unknown lines reach their maximum, we have indicated to us a *plus* pulse or condition of temperature. When the known lines reach their maximum, we have a *minus* pulse or condition of temperature.

During the period in which these observations have been carried on—that is, since 1879—three such crossings have occurred, indicating the presence of mean solar temperature conditions, in the years 1881, 1886-7 and 1892. Another crossing should have occurred in 1897, indicating thereby the arrival of another mean condition of the solar temperature, but as yet no such crossing has taken place.

Many sun-spots, then, must be held to indicate an excess of heat *and a very great excess.* In other words, the changes of solar temperature accompanying the sun-spot cycle are very much greater than was formerly imagined.

During the period in which these chemical inquiries into sun-spots have been pursued, we have learned a great deal about the solar prominences; and here again the same conclusions must be drawn from these observations—namely, that the sun is very much hotter at sun-spot maximum; and, indeed, the evidence here is more direct. We see a sun-spot easily because it appears dark on a bright surface, but it appears dark because it is cooler; hence, at first, spots were regarded as screens, and it was thought that, the more spots, the less the heat received from the sun. But the prominence work has taught us that the easily seen spot is only a feeble indication of tremendous solar activity and disturbances, which it is very difficult to see, for the reason that the disturbed areas are *brighter* than the general surface of the sun. Thanks, however, to a beautiful method invented by Messrs. Hale and Deslandres, based upon an idea of Janssen's, it is now pos-

sible, day by day, to secure a photographic picture of the sun's disc, showing both spots and prominences on which the former, the cooler phenomena, are seen, *"rari nantes in gurgite vasto"* of a disturbed sea of incandescent vapors stretching right across the sun's surface.

In such photographs, near sun-spot maximum, the concentration of the prominences in zones parallel to the equator is perfectly obvious at a glance. They are thus seen to cover a much larger area than the spots, so that we have the maximum of solar activity indicated, not so much by the increased absorption phenomena indicated by the greater number of the spots, but by the much greater radiation phenomena of the metallic prominences. There seems little doubt that, in the future, the measure of the change in the amount of solar energy will be determined by the amount and *locus* of the prominence area.

Spots are, therefore, indications of excess of heat, and not of its defect, as was suggested when the term "screen" was used for them. We know now that the spots at maximum are really full of highly heated vapors produced by the prominences, which are most numerous when the solar atmosphere is most disturbed. It is all the more necessary to point this out, because the insignificance of the area occupied by the spots has been used as an argument against any easily recognized connection between solar and terrestrial meteorological changes.

Assuming two belts of prominences N. and S. 10° wide, with their centres over lat. 16°, the sixth of the sun's visible hemisphere would be in a state of disturbance.

Both the inquiry into the chemical nature of spots and the study of prominences during the last quarter of a century have, it will be seen, demonstrated that there is an undreamt of rise of solar temperature at the maximum, and a considerable falling off at the minimum, of the sun-spot cycle.

I have before stated that the regularity of the widened-line record since 1879 was broken about the year 1897. The "crossing" we had a right to expect did not take place; something abnormal was occurring in the sun.

At the same time, irregularities in the Indian rainfall, accompanied by severe famines, were recorded. The coincidence seemed to me very striking, and it suggested the study and correlation of the various series of facts which might be expected to

throw light upon the subject, especially as we had now several new solar factors to deal with, revealed by the recent work to which I have referred.

Hence it was that the work* was undertaken, of which the Editor of the NORTH AMERICAN REVIEW has asked me to give a short account in the present article. This work has consisted, in a word, of a comparison of solar and terrestrial weather for a period for which the data along both lines are more or less complete.

Let me take the solar facts first.

A mean condition of solar temperature has been found from the equality in the numbers of the iron and unknown lines for the years 1881, 1886 and 1892; by extrapolation, it seemed that we might be justified in assuming other mean temperatures in 1869 and 1876.

With regard to the sun-spot cycle of eleven years, or thereabouts, which brings before us the main changes in the meteorology of the sun, it has long been known that a cycle of solar weather begins in about lat. 32° N. and S., and in a period of eleven years ends in about lat. 5° N. and S. Just before one cycle ends, another commences. The greatest amount of spotted surface occurs when the solar weather-changes produced in the cycle reach about lat. 16° N. and S.

The following table correlates the times of mean solar temperature, and of the *plus* and *minus* heat pulses, with the solar weather cycle, in order to arrive at the temperature history of the sun during the period which now concerns us:

SOLAR CYCLES.

Mean Lat. of spots.	19°		12°		18°		10°		19°	
Heat condition.	mean	plus	mean	minus	mean	plus	mean	minus	mean	plus
Years.	1869	1870-5	1876	1877-80	1881	1882-6	1886-7	1888-91	1891-2	1892

With regard to the terrestrial facts, it will be clear from the foregoing that the object to be pursued was to endeavor to ascertain if the *plus* and *minus* temperature pulses in the sun were echoed by *plus* and *minus* pulses of rainfall.

The Indian rainfall was selected (1.) because in the tropics

* "Solar Changes of Temperature and Variations in Rainfall in the Region Surrounding the Indian Ocean." By Sir Norman Lockyer, K. C. B., F. R. S., and W. J. S. Lockyer, M. A. (Camb.), Ph. D. (Gott.).

we may expect the phenomena to be the simplest, (2.) because the regularity of the Indian rains had broken down precisely when the widened-line observations showed a most remarkable departure from the normal, and (3.) because Blandford's Memoir on the Indian rainfall was the most extensive and complete at our disposal, being quite complete for the period of 1876-1886, while other rainfalls were available for subsequent years.

But even then, as I have stated, we had only the complete observed sun-spot areas from 1878 and the widened-line work from 1879.

I am most anxious to show how limited the inquiry has necessarily been, both as to place and time, because, on the one hand, my son and myself have been blamed for using too short a period, and, on the other, our conclusions have been considered general for the whole surface of the planet.

A preliminary study of Blandford's tables suggested even a further limitation. As it was important to deal with the individual observations as far as possible, because it was of the essence of the inquiry to trace the individual pulses if they were found, the southwest monsoon was, in the first instance, considered by itself, because, although Eliot holds that the winter rains (northeast monsoon) are due to moisture brought by an upper southwest current, their incidence is very different, and their inclusion might mask the events it was most important to study.

It soon became evident that the facts, when thus appealed to, showed that in many parts of India the *plus* and *minus* conditions of solar temperature were both accompanied by pulses producing pressure changes and heavy rains in the Indian Ocean and surrounding land. These occurred generally in the first year following the mean condition of solar temperature, that is in 1877-8 and 1882-3, dates approximating to, but followed by, the minimum and maximum periods of sun-spots respectively.

This was a revelation, and by no means in accord with a widespread idea that maximum sun-spots were alone accompanied by maximum rainfall, although Meldrum, as far back as 1881, referred to "the extreme oscillations of weather changes in different places, at the turning points of the curves representing the increase and decrease of solar activity."

It was especially in regions, such as Malabar and the Konkan,

where the monsoon strikes the west coast of India, that the sharpness and individuality of these pulses was the most obvious.

One method of study employed was based upon Chambers's view that the southwest monsoon depends upon the oscillations of the equatorial belt of low pressure up to 31° N. lat. at the summer solstice. The months of rain-receipt on the upward and downward swing will, therefore, depend on the latitude, and these months alone were considered.

The results obtained by this method of investigation are entirely in harmony with the above stated general conclusion, which, I must remind the reader, is based on the years 1876-1886, embracing one maximum and one minimum of sun-spots.

But we could go further than this, because Eliot, the Director General of the India Meteorological Department, had quite recently published a table of rainfall between 1875 and 1896 for the whole of India. This period embraced two maxima and two minima of sun-spots, and thus gave us a base double the length of that previously employed. Still, as it included the rainfall both of the southwest and northwest monsoons, it was anticipated that such a table, built up of means observed over such a large area and during both monsoons, would more or less conceal the meaning of the separate pulses observed in separate localities; this we found to be the case. Nevertheless, the table helped us greatly, because it included the summation of results nine years later than those included in Blandford's masterly memoir. Predominant pulses were found in 1889 and 1893, following those of 1877-8 and 1882-3. So that it enabled us to follow the working of the same law through another sun-spot cycle, the law, that is, of the mean solar temperature being followed by a pulse of rainfall.

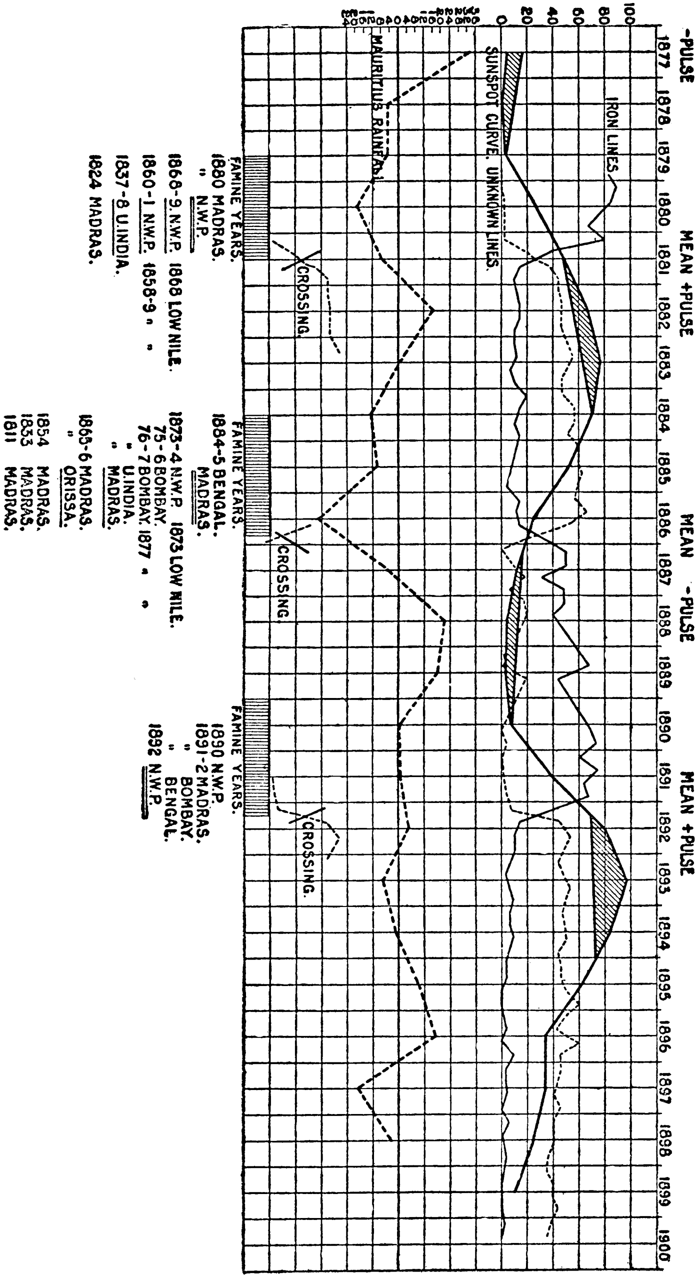
Years of Mean Solar Temperature	Years of Chief Rainfall
1876	1878
1881	1882
1886–7	1889
1892	1893

The pulses in the period stand as follows:

Sun-spot	Rain Percentage Variation	Solar Heat Pulse
Min. 1878	+ 15	−
Max. 1882	+ 6	+
Min. 1889	+ 6	−
Max. 1893	+ 22	+

Years after rise of iron lines

Years after rise of unknown lines


-PULSE
MEAN +PULSE
MEAN -PULSE
MEAN +PULSE
1877
1878
1879
1880
1881
1882
1883
1884
1885
1886
1887
1888
1889
1890
1891
1892
1893
1894
1895
1896
1897
1898
1899
1900
100
80
60
40
20
0
IRON LINES
SUNSPOT CURVE. UNKNOWN LINES.
MAURITIUS RAINFALL.
CROSSING.
CROSSING.
CROSSING.
FAMINE YEARS.
1880 MADRAS.
" N.W.P.
1868-9 N.W.P. 1868 LOW NILE.
1860-1 N.W.P. 1858-9 " "
1837-8 U.INDIA.
1824 MADRAS.
FAMINE YEARS.
1884-5 BENGAL.
MADRAS.
1873-4 N.W.P. 1873 LOW NILE.
75-6 BOMBAY.
76-7 BOMBAY. 1877 " "
" U.INDIA.
" MADRAS.
1865-6 MADRAS.
" ORISSA.
1854 MADRAS.
1833 MADRAS.
1811 MADRAS.
FAMINE YEARS.
1890 N.W.P.
1891-2 MADRAS.
" BOMBAY.
" BENGAL.
1892 N.W.P.

The variations in the intensities of the pulses of rain at the successive maxima and minima are very remarkable, and suggest the working of a higher law, of which we have other evidence.

The facts, then, showed conclusively that there was an excess rainfall in India following the times of mean solar temperature; in other words, about the time of maximum and minimum sun-spots.

Now, these pulses of excess rainfall are limited in duration. Hence, when each pulse ceases, the quantity of rain which falls in the Indian area is greatly reduced.

The next question, then, was to see whether there was any connection between the intervals between the pulses and the occurrence of the droughts and famines which have devastated India from time to time, and apparently without any periodicity enabling them to be foretold and provided against.

For this purpose, the sun-spot area and widened-line curves were brought together, and the mean solar temperature and the plus and minus conditions marked, over the years included in the inquiry. These are shown on the top of the accompanying diagram, on which the sun-spot curve is shaded for the years when the highest rainfall occurred.

Then the famine statistics were inquired into, and for this the tables given in the Reports of the Famine Commission were utilized.

The first result was that, during the period embraced in the inquiry, the non-shaded parts of the sun-spot curves—that is, the intervals between the rain pulses—were precisely the years of droughts and famines, 1880, 1884-5 and 1890-1.

The next result was, that the famines which had occurred between 1811 and the beginning of the period covered by the inquiry, all fell on, or nearly on, the same intervals, counting back eleven years either from 1880 or 1885, the central years of the intervals between the pulses.

Now, all this cannot be coincidence. It really looks as if these inquiries, carried on for some few years during which work shall be redoubled in obtaining the necessary solar and terrestrial data, may eventually provide us with materials for a more or less perfect prediction of Indian famines.

The Indian area, after all, is but a small part of the earth's surface; and when the tropics are left behind, the great irregu-

larities observed in weather changes are certain to make the problem a very difficult one.

Some other rainfalls have been examined outside the Indian area, and in some the same rain pulses have been recognized—the Nile and Mississippi valleys may be mentioned; but in other regions the rain pulses observed in India are lacking.

Such work as this would hardly be worth the doing if it did not suggest matter for further inquiries. The idea that the greatest rainfall should occur at sun-spot maximum was, perhaps, one founded on the magnetic results which were greatest at maximum; but why there should be two rain pulses in each cycle is not obvious at first sight.

Mr. Eliot long ago conjectured that the rainfall of India was profoundly modified by events taking place from time to time in the Southern Ocean. In his "Annual Summary" for 1896 he wrote as follows:

> "It has apparently been established in the discussion that the variations of the rainfall in India during the past six years are parallel with, and in part, at least, due to, variations in the gradients, and the strength of the winds in the southeast trade regions of the Indian Ocean. The discussion has indicated that there are variations, from year to year, in the strength of the atmospheric circulation obtaining over the large area of Southern Asia and the Indian Ocean, and that these variations are an important and large factor in determining the periodic variations in the rainfall of the whole area dependent on that circulation, and more especially in India. It has also been indicated that these variations which accompany and are probably the result, in part, of abnormal temperature (and hence pressure) conditions in the Indian Ocean and Indian monsoon area, may be in part due to conditions in the Antarctic Ocean, which also determine the comparative prevalence or absence of icebergs in the northern portions of the Antarctic Ocean."

We have begun an investigation into the pressure changes which have been recorded in this region, the idea underlying the inquiry being, that the reduced solar temperature may modify the pressure, so that the high-pressure belts south of Mauritius may be broken up and thus allow cyclonic winds from a higher latitude to increase the summer rains, as they certainly were increased at the normal minima of 1877 and 1888. If anything like this turns out to be true, the whole question of atmospheric circulation is involved; and it may be that, eventually, the study of the rain pulses in different latitudes and longitudes will help us greatly in following what goes on in the upper air.

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